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High Temperature Superconducting State in Metallic Nanoclusters and Nano-Based Systems

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14. ABSTRACT

Main goal of project is the search of new materials with high temperature of the superconducting transition (order of room temperature). Main investigation objects are special nanoclusters with shell structure of the electron spectrum. The goal is investigation of the possibility of building of nets (two and three dimensional) from nanoclusters with high value of the superconducting transition temperature and possessing of possibility to transfer high value of transport current without dissipation of energy. Thermal and quantum fluctuations are source of energy dissipation. The net from nanoclusters is inhomogeneous media. Intrinsic inhomogeneity leads to pinning of vortices and make it possible to flow of non dissipative current. Our goal is investigation of creep of the vortex structure in high and low temperature region. Main investigation methods are methods of quantum field theory. Expected results are: we are hope obtain nanoclusters with high value of the superconducting transition temperature and determine physical parameters of such clusters (chemical structure, form of cluster, electrons number, etc.). We are anticipating that for special conditions the resonant tunneling between nanoclusters can take place and as result the critical value of the superconducting current density will increase strictly. This will lead also to the strong suppression of the role of thermal and quantum fluctuation.

15. SUBJECT TERMS

EOARD, Materials, Superconductivity, Tunneling, Resonance Tunneling, Clusters, Nanoclusters, Superatoms

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ISTC Project No. 4084p (EOARD N 097006)

High Temperature Superconducting state in metallic Nanoclusters and nano-Based Systems

Unrestricted Summary of Technical Report

on the work performed from October 1 (2010) years to September 30 (2011) years

Authorized for publication

Institution of Russian Academy of Sciences L.D.Landau Institute for Theoretical Physics RAS

Project Manager	**Ovchinnikov Yury Nikolaevich Doctor of Phys.-math. Sciences**	**5/10/2011** Ya. Ovchinnikov
Director	**Lebedev Vladimir Valentinovich Doctor of Phys.-math. Sciences Corresponding member of RAS**	**5/10/2011**

Project number: N 4084p (EOARD N 097006)

Title of the Project: High Temperature Superconducting state in metallic Nanoclusters and Nano-Based Systems

Project Manager: Ovchinnikov Yury Nikolaevich

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Objectives / scope of work and technical approach / expected results

Main goal of project is the search of new materials with high temperature of the superconducting transition (order of room temperature). Main investigation objects are special nanoclusters with shell structure of the electron spectrum. The goal is investigation of the possibility of building of nets (two and three dimensional) from nanoclusters with high value of the superconducting transition temperature and possessing of possibility to transfer high value of transport current without dissipation of energy. Thermal and quantum fluctuations are source of energy dissipation. The net from nanoclusters is inhomogeneous media. Intrinsic inhomogeneity leads to pinning of vortices and make it possible to flow of non dissipative current. Our goal is investigation of creep of the vortex structure in high and low temperature region. Main investigation methods are methods of quantum field theory. Expected results are: we are hope obtain nanoclusters with high value of the superconducting transition temperature and determinate physical parameters of such clusters (chemical structure, form of cluster, electrons number et all). We are waiting, that for special conditions the resonant tunneling between nanoclusters can take place and as result the critical value of the superconducting current density will increase strictly. This will leads also to the strong suppression of the role of thermal and quantum fluctuation.

Obtained results

New examples of nanoclusters with high value of the superconducting transition temperature are found. We have obtained, that not only magic or near magic nanoclusters of special size are perspective samples to obtain the high value of superconducting transition temperature, but also clusters with half filled upper shell. In such type of clusters the new phenomena is possible-the superconducting transition can start to be the first order phase transition. Investigation in this region will be continued. For practical use it is very important to have macroscopic samples with superconducting properties. Such objects are nets constructed from nanoclusters (two and three dimensional). Essential question for use of nets is energy dissipation, connected with thermal and quantum fluctuations. We got, that amplitude of the superconducting current between nanoclusters can exceed on the several orders the quasi classical expression for current value between massive superconductors.

It was found, that for special conditions the resonant tunneling take place between nanoclusters, and amplitude of resonant current exceeds for several orders of magnitude the non resonant contribution to the full current value. We got, that for realistic distances between

nanoclusters, the density of the superconducting current can reach the giant value order of 10^9am/sm^2, even in non resonant conditions. It is essential, that inhomogeneity of the nets leads to the intrinsic pinning strong enough to make the energy dissipation negligible small. The temperature To of the transition from thermal activation (Arrenius law) to the macroscopic tunneling regime was found.

The investigation of the nonlinear equations of the type of the time dependent Ginzburg-Landau equations and appearing to it singularity of different kind for finite time was continued.

Some part of results was published. Some other part is at stage of prepare to publication.

Keywords:
Superconductivity, tunneling, creep, resonance tunneling, clusters, nets, fluctuations, phase transitions.

ISTC № 4084p (EOARD N 097006)

High Temperature Superconducting state in metallic Nanoclusters and nano-Based Systems

Final Project Technical Report

on the work performed from October 1 (2010) years to September 30 (2011) years

Institution of Russian Academy of Sciences L.D. Landau Institute for Theoretical Physics RAS

Project Manager	**Ovchinnikov Yury Nikolaevich Doctor of Phys.-math. Sciences**	**5/10/2011**
Director	**Lebedev Vladimir Valentinovich Doctor Phys.-math. Sciences, Corresponding member of RAS**	**5/10/2011**

Title of the Project:	High Temperature Superconducting state in metallic Nanoclusters and nano-Based Systems
Commencement Date:	October 1 2010 year
Duration:	1 year (to September 30 2011)
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Participating Institutes:	not
Foreign Collaborators:	Partner EOARD

Keywords: superconductivity, tunnelling, nanocluster, fluctuations, critical current, dissipation

LIST OF CONTENTS

The project is concerned with new materials which are characterized by high temperature of the superconducting transition (potentially, room temperature). Nanoclusters with shell structure of the electron spectrum have been studied. In addition, we have studied the possibility of building of nano-based networks transferring a high value of dissipationless current. The sourses of energy dissipation are the thermal and quantum fluctuations.

The methods of modern quantum field theory are employed.

Simultaneously the solution of nonlinear equations of the type of time dependent Ginzburg-Landau equation will be investigated. Main purpose is to study the development of singularities of different kinds in such solutions for finite time.

As a first step, the Josephson tunneling between two nanoclusters was analyzed. It was shown that there is a new additional channel (resonant tunneling) can increase the amplitude of the current. Then the tunneling networks have been analyzed. They appear to be stable with respect to fluctuations. Moreover, one can prove that such networks can transfer a large critical current; this feature is very interesting from the point of view of various applications.

New family of nanoclusters is investigated and conditions are found, leading to high value of superconducting transition temperature.

1. Brief description of the work plan: objective, expected results, technical approach

The following problems have been addressed:
1. Nano-based tunneling networks. Tunneling current.
2. Resonant tunneling.
3. Search of new systems with high value of superconducting transition temperature.
4. Investigation of nonlinear equations of the type of time dependent Ginzburg-Landau equation, study of development in such solutions of the singularities of different kind.

2. Method, Experiments, Theory etc.

The methods of modern quantum field theory are employed.

3. Results

We studied the tunneling networks formed by superconducting nanoclusters (e.g., by Al_{56} clusters).. It has been demonstrated that such networks are capable to transfer a high density current (up to 10^7A/sm^2) . We studied possible channels of dissipation, especially impact of vortices and prove that the high current state is stable , so that it is, indeed, possible to transfer a large superconducting current at high temperatures. In such a way the influence of quantum and thermal fluctuations was analyzed. It is important that under special, but realistic conditions one can observe the resonant tunneling between nanoclusters, and this is accompanied by large increase in the current amplitude . The current can reach the values of order of 10^9 Am/sm^2 . These results are very promising from the point of view of various applications .

The time dependent Ginzburg-Landau equation was employed to study the relaxation phenomena. The new results describing the collapse phenomenon are obtained.

4. Conclusion

The superconducting state of small metallic nanoclusters can be used in order to build tunneling networks which are capable to transfer high density superconducting current at high temperatures. The main results are published or submitted for publication. They have been presented at the APS Meeting
(invited talk) and several international conferences.

There are still several interesting challenges. Among them the study of the a.c response,search for new nano superconducting systems, and we hope to continue this exciting research.

5. References

Attachment 1: List of published papers and reports with abstracts

1. Yu.N.Ovchinnikov and V.Z.Kresin "Theoretical Investigation of Josephson Tunneling between Nanoclusters" Phys.Rev.B81,214505(1-6) (2010)

Josephson tunneling between nanoclusters is analyzed. The discrete nature of the electron energy spectra, including their shell ordering, is explicitly taken into account. The treatment considers the two distinct cases of resonant and non resonant tunneling. It is demonstrated that the current density greatly exceeds the value discussed in the conventional theory. Nanoparticles are shown to be promising building blocks for nanomaterials based tunneling networks.

2 . Yu.N.Ovchinnikov and V.Z.Kresin "Josephson effect between Nanoclusters in Resonance Conditions" JETP 111,82-96 (2010)

A general expression is derived for the Josephson current between nanoclusters. It is shown that in the resonance conditions between electron levels of clusters, the expression for the current obtained in the tunnel Hamiltonian model becomes invalid. In the case of degeneracy or close to degeneracy of energy levels in isolated clusters, the critical Josephson current may exceed the value obtained in the model of tunnel Hamiltonian in the large parameter, viz., the ratio of the order parameter "delta" to the distance between the resonance level and the levels closest to it.

3. Yu.N.Ovchinnikov and I.M.Sigal "Long Time Relaxation Processes in the Nonlinear Schrodinger Equation" JETP 112, 469-478 (2011).

The nonlinear Schrodinger equation, known in low-temperature physics as Gross-Pitaevskii equation, has a large family of excitations of different kinds. They include sound excitations, vortices, and solitons. The dynamics of vortices strictly depends on the separation between them. For large distances, some kind of adiabatic approximation can be used. We consider the case where an adiabatic approximation can be used (large separation between vortices) and the opposite case of a decay of the initial state, which is close to the double vortex solution. In the last problem, no adiabatic parameter exist (interaction is strong) . Nevertheless, a small numerical parameter arises in the problem of the decay rate, connected with an existence of a large centrifugal potential, which leads to a small value of the increment. The properties of the nonlinear wave equation are briefly considered in the Appendix A.

4. B.L.Jonsson, Yu.N.Ovchinnikov, I.M.Sigal, and F.S.T.Ting "Dynamics of breakup of multiple vortices in Gross-Pitaevskii equation of superfluids" Journal of Mathematical Physics 52, 093505(1-16) (2011)

In this paper we study the Gross-Pitaevskii equation of the theory of super fluidity, i.e. the nonlinear Schrodinger equation of the Ginzburg-Landau type. We investigate the dynamics of the breakup of the double vortex. More specifically, we prove instability of the double vortex, compute the complex eigenvalue responsible for this instability, and derive the dynamical equation of motion of (center of) single vortices resulting from splitting of the double vortex. We expect that our analysis can be extended to vortices of higher degree and to magnetic and Chern-Simmons vortices.

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5. Yu.N.Ovchinnikov ,I.M.Sigal "On collapse of wave maps" Physica D240, N17, 1311-1324 (2011).

We derive the universal collapse law for semilinear wave equation, that has non- normalized zero mode. To do this we introduce a nonlinear hree parameters transformation from original variables to blowup ones. Our derivations are confirmed by numerical simulations.

6. Yu.N.Ovchinnikov, I.M.Sigal "Mean curvature flow of a hyperbolic surface"
JETP 113 N4 (2011)

A four-parameter family of self-similar solutions is obtained to the mean curvature flow equation for a surface. This family is shown to be stable with Respect to a small deformation of a hyperbolic surface. At time instant t*, a singular point is formed within a finite time interval, that is accompanied by a change in the topology of the surface. The solution is continued beyond the singular point. A relationship between the parameters describing the hyperbolic surface before and after the change in the surface topology is obtained. A particular case is analyzed when the unperturbed surface is a cylinder. A cylindrical surface is weakly unstable with respect to a perturbation in the form of a "wide neck". At the final stage of the shrinking of the neck when its transverse size becomes much less than the cylinder radius at large distances from the neck, the surface flow in a wide region in the neighborhood of the neck is described by a universal two-parameter family of self-similar solutions. These solutions are stable with respect to small perturbations of the surface,

7. Yu.N.Ovchinnikov, V.Z.Kresin "Artificial nets from superconducting nanoclusters" to be published in JETP (2012)

In the present paper we show that large transport current can flow through superconducting nets composed of nanoclusters. Although thermal and quantum fluctuations lead to a finite value of dissipation in one and two-dimensional systems, this value may be very small for realistic parameters of the nanoclusters and distances between them. The value of action for vortex tunneling at zero temperature can be made sufficiently large to make the dissipation energy negligibly small. We estimate the temperature To of the transition from the thermal activation to quantum tunneling.

Attachment 2: List of presentations at conferences and meetings with abstracts

1. Troizk , Institute of Physics of High Pressure RAS, June 2011
"Strong correlated electron systems and quantum critical phenomena"
Yu.N.Ovchinnikov and V.Z,Kresin "Josephson effect between nanoclusters in resonance conditions".

A general expression is derived for the Josephson current between nanoclusters. In the case of degeneracy or close to degeneracy of energy levels of electrons in isolated clusters the critical current value may exceed the value in the model of tunnel Hamiltonian in the large parameter , vis., the ratio of the order parameter "delta" to the distance between the resonance level and the levels closest to it.

2. Chernogolovka, L.D.Landau Institute for Theoretical Physics RAS, July 2011
"100 –years, A.B.Migdal"
Yu.N.Ovchinnikov, V.Z.Kresin "Superconductivity in nanoclusters and nanosystems".

The value of the superconducting transition temperature is investigated in nanoclusters, having shell structure of electronic spectrum. The giant increasing of the Tc was found in special magic, near magic clusters and clusters with half filled upper shell (relative bulk samples).. Nanoclusters are shown to be promising building blocks for nonomaterials-based tunneling networks.

Attachment 3: Information on patents and copy rights (List and describe patents and copyrights which were obtained or may be obtained as a result of the project)

Application on patent did not sent.